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Study on Sliding Characteristics and Controlling Measures of Colluvial Landslides in Qinghai-Tibet Plateau

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Abstract

Most landslides in Qinghai-Tibet Plateau take place in the Quaternary strata. Reasonable deformation mechanism, analyses method and controlling measures are proposed to treat colluvial landslides in this paper. Combined with the regional geological conditions of a colluvial landslide located at Road S101 Line of Qinghai Province, distinctive influencing factors were analyzed, including adverse physical and mechanical properties, geometrical structure, coupled fluid and thermal process. Slope stability was simulated by finite difference method. Displacement and shear strain in the lower part of sliding body are both higher than the upper part in saturated condition, consistent with the actual sliding characteristics. According to the geological comprehensive analyses and numerical simulation, the deformation mechanism, temporal and spatial evolutionary processes were summarized. The results show that freeze-thaw cyclic process of stagnant water during winter and spring make shallow deposits creep continuously and slide ultimately. Saturated condition caused by rainstorm in summer or autumn makes the slope slide integrally, and draws the mudstone at back to slide subsequently. The suitability and practical feedback of various kinds of controlling measures applied to colluvial landslides in cold regions were discussed. Micropile has significant elastic flexibility and unloading ability, and so can adapt to the mechanical change and sliding process of slope during freeze-thaw process. Both practical application and numerical calculation indicate that micropile is an appropriate choice against colluvial landslides in Qinghai-Tibet Plateau.

Keywords: Qinghai-Tibet Plateau, colluvial landslide, freeze-thaw cycle, evolutionary process, micropile

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1 Introduction

Due to the strong uplift in history, tectonic movement of Qinghai-Tibet Plateau is forceful. Added with the action of bad climatic conditions, various geological hazards including slope collapse, landslide, debris flow, etc., are all frequent and large-scale, making Qinghai-Tibet Plateau become one of the regions with serious geological disasters in China (Peng et al., 2004). Superimposed statistical data of disaster cases and corresponding epoch strata indicate that most geological disasters in Qinghai-Tibet Plateau take place in the Quaternary Strata (Jiang et al., 2005). Along with the infrastructures constructed massively, geological disasters and engineering problems related to the Quaternary deposits are becoming more prominent. Among various geological disasters in Qinghai-Tibet Plateau, colluvial landslides are especially widely distributed with high frequency and great harm, and are also different from those in ordinary regions (Li et al., 2005).

In Qinghai-Tibet Plateau, the modes of landslides in permafrost regions are quite different from those in seasonal frozen soil region, and have been studied as a special kind separately (Jin et al., 2005). The colluvial landslides mentioned in this paper mainly refer to those happened in seasonal frozen soil region, and some relevant researches have also been carried out (Gu et al., 2009; Wu et al., 2010). The above researches all point out that the coupled fluid and thermal process is the main factor of colluvial landslides. However, due to the method of stability analyses and controlling design are still referred from the general landslides, many failure cases still appear after treatment (Yang et al., 1998). Therefore, it is necessary to analyze the distinctive geological and climatic conditions, temporal and spatial evolutionary process, deformation mechanism and effective controlling measures of colluvial landslides in Qinghai-Tibet Plateau.

Taking a colluvial slope located at the Road S101 Line of Qinghai Province as research case, this paper analyzed its geometrical structure and distinctive influencing factors on the basis of detailed geological survey. Distribution of its displacement and shear strain in both stable and saturated state caused by coupled fluid and thermal process were simulated by the finite difference software FLAC^{3D}. Then the complete evolutionary process, sliding mechanism and deformation characteristics of colluvial landslides in Qinghai-Tibet Plateau were deduced through both geological discrimination and numerical simulation. In addition, the suitability and practical feedback of various kinds of controlling measures against such landslides were discussed. At last, the feasibility of micropile applied in prevention of colluvial landslide in Qinghai-Tibet Plateau was demonstrated.

2 Engineering Case

2.1 Geological Conditions

The Road S101 Line of Qinghai Province locates in eastern mountainous area of Qinghai-Tibet Plateau. Among its Amao Pass~Dawu section located at Maqin County of Tibetan Autonomous Prefecture of Golog, roadbed of K359+881~+929 passes through a colluvial slope, in form of half-fill and half-dug, as shown in Figure 1. After completion, slide took place in this slope, leading to many radial cracks that can be seen clearly nearby the roadbed. Drainage ditch was extruded to bulge, threatening the normal traffic of the S101 Line.

The landslide locates at an ancient trench with both sides attached to the nearly north-south bedrock ridge, and its boundary is like a round-backed armchair. Two exports can be seen clearly at the leading edge of slope outside the roadbed, including the shallow one and the deep one. The strata in landslide area mainly include the Quaternary deposits and mudstone of the Gui-de Group of Tertiary Oligocene Epoch. Deposits are consisted of purplish-red sand clay and gravel soil, in which breccia content can be 10%~40%. Purplish-red mudstone is controlled by medium-thick lamellar

structure. As illustrated in Figure 2, in north is the Lajiasi Fault (F1), in south is the Naheqiaogai Fault (F2), and in east is one north-south fault (F3). Affected by above faults, structural fractures are developed in slope, so the mudstone is broken and easy to be permeated by groundwater.

In geographical position, landslide area locates at the “Three-River Source Region” that is known as “Chinese Water Tower”. The climatic condition is cold and wet, with annual average temperature below -4°C and large temperature difference between day and night. The annual rainfall amount is above 565mm, and rainstorm and hail in summer and autumn occur frequently. Ground water includes perched water in loose deposits and fissure water in bedrock. Water level is shallow and water content of sliding body is high. The strength of mudstone is high, while its fractures facilitate the water permeability.

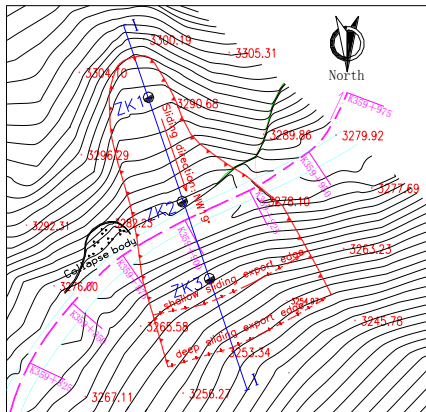


Fig.1 Engineering geology plan of landslide area **Fig.2** Schematic diagram of geological structure

2.2 Slope Structure

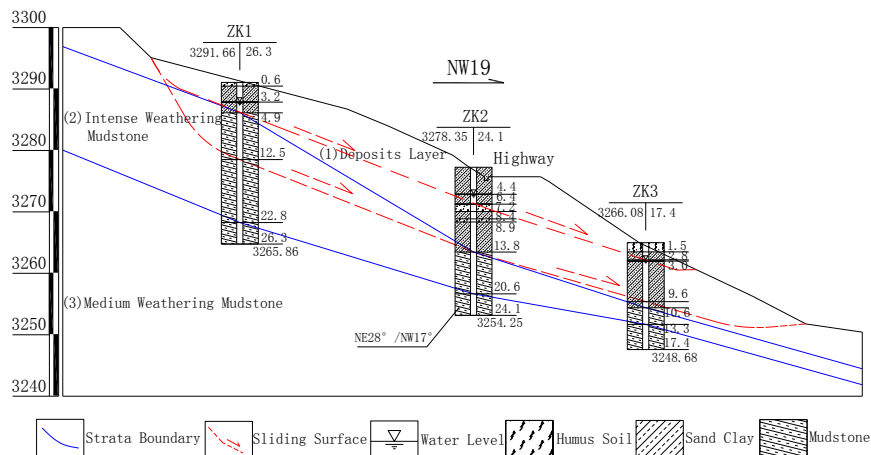


Fig.3 Geological section of I-I site of colluvial landslide (unit: m)

According to the exploration results, two obvious sliding scratches could be seen at different depth in ZK1~ZK3, as is shown in Figure 3. Water content at depth of 4.9m in exploratory drilling hole No.1 (ZK1) was high, and the soil around this depth was softened obviously, so were 6.4m deep in ZK2 and 2.8m deep in ZK3. Thus the sliding body could be divided into two layers including the shallow one and the deep one. Shallow landslide slipped along the phreatic line in colluvial layer, with length of 90m and maximum depth of 6m. The deep landslide slipped along the contact interface with the

underlying bedrock, and drew the intense weathering mudstone at back to slide subsequently, with length of 107m and maximum depth of 13.8m. Volume of the shallow sliding part is about $2.5 \times 10^4 \text{m}^3$, and the deep one is about $5.5 \times 10^4 \text{m}^3$, both belonging to minor landslides.

Based on the transmitting coefficient method appended by 《Specification of Geological Investigation for Landslide Stabilization》(DZ/T0218—2006), stability coefficient of shallow sliding body was 0.99, and the deep one was 1.05.

2.3 Influencing Factors of Stability

According to the geological analyses above, the distinctive influencing factors of colluvial landslides in Qinghai-Tibetan Plateau can be summarized as the following four aspects: (1) The genesis, composition and structure of the Quaternary deposits are always unfavorable to slope stability. (2) Affected by tectonic movements, occurrence of the Tertiary strata is always disordered and the angles of monoclinic structural planes change a lot, some of them are steep. (3) The water content of shallow deposits gradually increase under the action of moisture aggregation caused by temperature difference in freezing period, then the frozen soil will melt quickly to be saturated in thawing period. (4) Affected by the rise of global temperatures, rainstorm is frequent in summer and autumn. So the seasonal freeze-thaw cycles and rainfall infiltrations make the physical and mechanical properties of deposits deteriorate continuously. In case of adverse geometric structure, large plastic or creeping deformation is easy to appear in slope driven by multiple effects of gravity and groundwater, becoming the main source of landslide.

3 Analyses of Landslide Characteristics

3.1 Method of Numerical Simulation

Considering the nonlinear properties of geotechnical materials, elastic-plastic constitutive relation was used in this calculation, its failure criterions are the combination of tensile yield criterion and Mohr-Coulomb shear yield criterion. The natural state refers to the state of lowest water content under evaporation in summer and autumn, and the saturated state refers to the completely melt state of frozen soil caused by coupled fluid and thermal process. According to the results of laboratory test, values of physical and mechanical parameters are in table 1 below. Initial stress field is calculated by elastic solution method and then two states including natural state and saturated state were calculated with displacement reset to zero firstly in a 5m wide 3D mesh model.

Strata	Density (kN/m^3)	Young's modulus (MPa)	Poisson ratio	Tensile strength (kPa)	Cohesion (kPa)	Internal friction angle ($^\circ$)
(1)	19.0/19.7	20/5	0.34/0.36	—	40/12	30.0/24.5
(2)	23.0/23.5	100/20	0.30/0.33	50/5	120/30	34.0/28.5
(3)	24.0/24.3	300/200	0.29/0.31	100/70	240/190	40.0/37.0

Note: the left of “/” are natural values, the right of “/” are saturated values.

Table.1 Physical and mechanical values of parameters in different conditions

3.2 Analyses of Numerical Results

3.2.1 Displacement Field

In natural state, displacement of potential sliding body is within 10mm. Displacement decreases gradually from surface to the deep range, mainly consisted of vertical deformation caused by gravity,

as shown in Fig 4 (a). In saturated state, displacement near the roadbed can reach about 1200mm, consistent with the actual settlement of subgrade and damage of drainage ditch. Contours of 400mm and 600mm distribute continuously within sliding body and interrupt at the leading edge of slope, as shown in Fig 4 (b). In addition, displacement trace indicates that sliding deposits draw the rear mudstone to slide obviously.

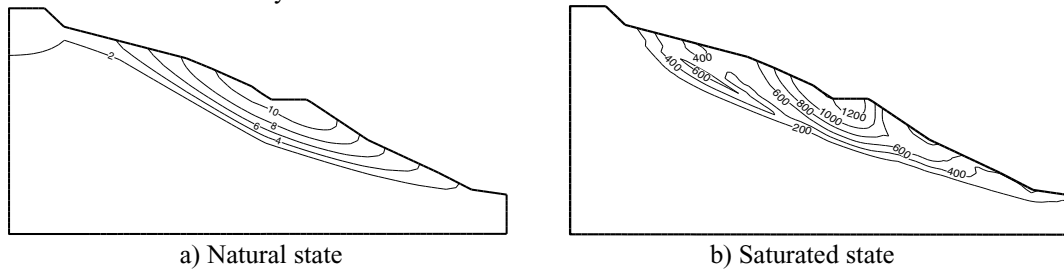


Fig.4 Displacement of central section (Unit: mm)

3.2.2 Shear Strain Field

In natural state, shear strain distributes among the sliding body uniformly, with the range of about $10^{-5} \sim 10^{-4}$. According to the change of plastic zone in calculation process, and the relationship between mechanical properties and shear strain of soil (Tu et al., 2010), the sliding body is mainly in the transition stage from elastic state to plastic state. There is slight strain concentration around the central anti-sliding section located at the thickest colluvial position, with the maximum value of 3.5×10^{-4} , as shown in Fig5 (a). In saturated state as shown in Fig5 (b), magnitude of shear strain distributes among sliding body are totally larger than 1×10^{-2} , judging for the plastic damage stage. There are two strain-extreme regions, which locate at the middle part and near the toe of the slope, corresponding with the lowest part of two sliding planes. Shear strain of the shallow sliding export gradually reached about 5.5×10^{-2} , which is larger than the strain value of 4×10^{-2} near the deep sliding part. The phenomena above indicate that the shallow landslide occurs firstly and is worse than the deep one. Shear strain around the trailing edge of sliding body is between $1 \times 10^{-2} \sim 2.5 \times 10^{-2}$, which is about $1/4 \sim 1/2$ of those in the front part, consistent with actual dominant tensile failure in trailing edge.

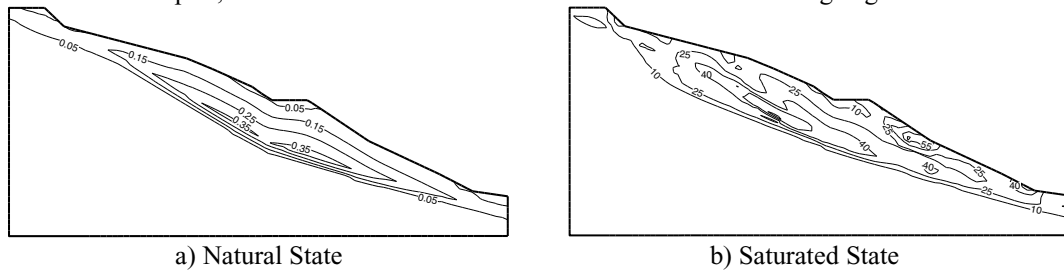


Fig.5 Shear strain of central section (Unit: 10^{-3})

Displacement and shear strain in the lower part of sliding body are both higher than the upper part. So it can be judged out that the overall deposits slide along the sliding surface firstly, then tract the intense weathering mudstone at back to slide subsequently, belonging to tractive landslide. So the geometric structure and mechanical property of the slope in saturated state are conducive to develop the actual two-layer sliding mode.

3.3 Evolutionary Process of Landslide

According to comprehensive geological analyses and numerical simulation, the whole evolutionary process of colluvial landslides in Qinghai-Tibet Plateau can be divided into four stages.

Stage I : groundwater accumulation. Due to the large rainfall concentrated in summer and autumn, level of groundwater rises after infiltration, leading to the increase of water content of deposits.

Stage II : groundwater redistribution caused by freezing. The deposits are in frozen state during winter and early spring night, and in thawing state during early spring daytime and summer. Under the action of moisture aggregation caused by temperature difference, the water content of shallow deposits is gradually larger than its original state.

Stage III : shallow landslide induced by thawing. The freeze-thaw cyclic process make the mechanical strength of deposits reduce continuously. When the high ice-content shallow deposits thaw rapidly and become saturated under the action of elevated atmospheric temperature or precipitation in spring and summer, it will creep downwards gradually and slide ultimately.

Stage IV: deep landslide induced by rainstorm. Under the heavy rainfall in summer or autumn, infiltration makes the water content of deposits increase rapidly, and the strength of contact interface between strata reduces a lot especially. Affected by the softening, weight increasing, and hydrodynamic pressure of groundwater, the whole deposits will enter the large deformation state.

So in Qinghai-Tibet Plateau, the evolutionary process of colluvial landslides in seasonal frozen soil region is complex, and their sliding mechanism, deformation characteristics and so on are all different from the gelifluctions and landslides in permafrost region. The shallow landslide case is judged for unstable sliding state, and the deep one is judged for relatively stable state of creeping extrusion.

4 Analyses of Controlling Measures

Controlling measures against landslides mainly include load reduction, retaining structures, anchoring structures, water-intercepting and drainage structures and so on, all with different applicable conditions (Wang et al., 2006). Freeze-thaw cycles and rainstorm infiltration are the main reasons for colluvial landslides in Qinghai-Tibet Plateau, so ground and underground water interrupting and drainage structures should be adopted preferentially.

In cold regions, earth pressure and frost heaving force will dominate alternately on retaining structures. According to the test in frost condition, the horizontal frost heaving force can be several times or even dozens of times larger than the earth pressure (Wang et al., 2010). Therefore, gravitational wall with poor resistance and other rigid structures that may block drainage paths are not suitable in cold regions. For colluvial slopes in cold regions, seasonal and diurnal freeze-thaw cycles make the loose deposits have certain rheological properties. Even under small load, internal structure of deposits may appear irreversible changes, causing the stress relaxation and creeping deterioration of slope. Therefore, anchoring structure is generally not suitable for loose colluvial slopes in cold regions. The practices have also proved that the cable engineering in Qinghai-Tibet Plateau always suffer from the problems of durability (Zhang et al., 2013). Anti-sliding pile with large section is the most effective measure for large-scale and deep landslides. But its construction needs artificial excavation, so it is time-consuming, cost expensive, and especially difficult to construct in water-rich strata. In addition, its linear layout with large spatial volume has high requirements with the density and deformation modulus of slope, so it is also not suitable for the loose colluvial slopes to some extent.

Micropile is also one kind of effective anti-sliding structure, whose diameter is generally less than 400mm. Because the high speed of mechanical construction, micropile can be drilled in arbitrarily angle and have strong adaptability to complex strata. Its spatial volume in slope is so small that it will not disturb the potential sliding body by destroying drainage paths during construction or blocking water from discharge. Micropiles are always arranged as plum-shaped multiple rows, and connected by the top beam as a whole to promote the fixity and bearing capacity (Sun et al., 2013). Due to large ratio of length and diameter, micropile can deform elastically and unload flexibly, adapting well to the mechanical change and deformation process of landslide during the freeze-thaw cycles. Its

construction style of cement grouting also has improving effect on the loose deposits. The micropile group retains as a dense wall, so its requirement related with physical and mechanical properties of slope are relatively low.

5 Retaining Effect of Micropile

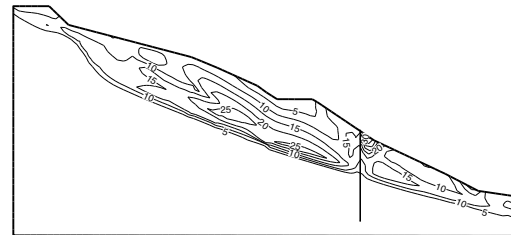
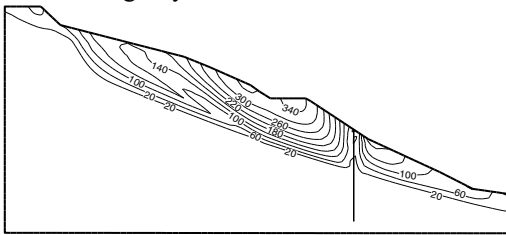
5.1 Scheme of Controlling Project

On the basis of geological exploration and stability analyses above, the controlling project was designed as follows: (1) chief frame structure of micropiles located at the leading edge of shallow landslide; (2) auxiliary blind drainage ditch located at both sides of subgrade. Micropiles are adopted as a plum-shaped two-row group, with diameter of 300mm and length of 20m, about 8m of which are embedded in the deep stable mudstone. Steel-reinforced concrete top beam with sectional dimension of 1m wide and 1m high is embedded into the micropiles for 0.5m deep. The spacing between micropiles is 0.5 m at the direction parallel to slide, and 1.0m at the direction perpendicular to slide.

In FLAC^{3D}, the micropiles and top beam are simulated by Pile unit and Beam unit. Node-node rigid connects are established between headpiece nodes of piles and coincident nodes of beams.

5.2 Retaining Effect

The calculation process of colluvial slope in saturated condition is convergent when reinforced by micropiles. As shown in Fig.6, the maximum displacement values near subgrade decrease obviously from 1200mm in saturated state to current 340mm. Dominant deformation direction transfers from the horizontal to the vertical. Deposits behind the micropiles deform in mode of horizontal compression. As shown in Fig.7, shear strains of sliding body behind micropiles distribute similarly with those in stable state. But due to the effect of weight increasing and softening caused by saturated condition, the strain values increase about 100 times, so the mechanical behavior of sliding deposits is changed to be the plastic stage. So even in the most unfavorable state, the slope reinforced by micropiles group does not slide integrally.



Tertiary strata is steep. Influenced by the cold climate, colluvial slopes are generally under special effects of seasonal and diurnal freeze-thaw cycles. Infiltration of frequent rainstorm in summer and autumn can lead to the quick increase of groundwater level. Affected by the multiple adverse conditions above, a large number of colluvial landslides are developing and deteriorating.

(2) For the landslide case, it suffers from the cyclic process of groundwater accumulation in summer and autumn→ freezing in winter→ thawing in spring. The shallow deposits deteriorate in internal structure and creep downwards continuously, ultimately the deformation accumulates to be shallow landslide. Heavy rainfall make the water content of deposits increase rapidly, and cause the effects of softening, weight increasing, hydraulic function and so on. The whole deposits then slide integrally, and draw the mudstone at back to slide subsequently. In sliding process, displacement and shear strain of the lower part are both higher than the upper part, consistent with the actual sliding characteristics, so belonging to the tractive-type landslide.

(3) Micropiles are always arranged in plum-shaped multiple rows and combined as a whole by the top beam with considerable anti-sliding capacity. They can be constructed at high speed by drilling machine, and will not disturb the slope excessively and not affect the normal discharge of groundwater. Most important of all, micropile can unload flexibly through recoverable elastic deformation, and adapt well to the thrust change caused by freeze-thaw cycles. Both practical application and numerical simulation in the controlling project of the landslide case indicate that micropile is rather an appropriate choice for landslides in cold regions.

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